DEFINING THE INTERDEPENDENCE OF VOLCANISM, TECTONISM, AND FLUID AVAILABILITY IN THE FORMATION OF EPITHERMAL MINERALIZATION AT AURORA-BODIE CA/NV USING AVIRIS DATA

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GEOLOGIC BACKGROUND AND RATIONALE FOR STUDY

Precious metal epithermal deposits have been studied extensively over the last 80 years and there is broad agreement that the circulation of large fluid volumes plays an essential role in their formation. This is also consistent with the premise that high-temperature geothermal systems are modern analogs of ancient epithermal systems. A link between the distribution of epithermal deposits and tectonic structures can also be made (Berger and Henley,1989). However, volcanism, tectonism, and fluid availability, if considered independently, cannot explain the occurrence and distribution of epithermal deposits. There is an essential interdependence between these three elements in the formation of epithermal systems that has not been thoroughly investigated.

We have integrated several lines of evidence from different localities to support the idea of interdependence between volcanism, tectonics, and fluid availability.
Evidence of the role of volcanism can be illustrated by examining the Great Basin. In the Great Basin the large volumes of Eocene-Oligocene volcanic rocks are rarely accompanied by epithermal mineralization. However, such mineralization is commonly associated with Miocene and younger volcanics, suggesting that volcanism must be only one factor in the development of the mineralized deposits. In another example, data from the Taupo Volcanic Zone (TVZ), New Zealand can be used to illustrate that tectonic setting is an important, but not exclusive, factor in the occurrence of geothermal systems. In the TVZ high-enthalpy geothermal activity is widespread, and commenced with the development of pull-apart basins bounded by crustal-scale faults. However, metalliferous geothermal systems are not randomly distributed along these structures, but are colinear along one boundary of the Taupo graben. As a third example, in the western United States the common association of epithermal deposits with lacustrine deposits and/or high altitude water sheds illustrates the importance of fluid availability in the mineralization process. We believe this association is genetic and that these reservoirs were necessary to provide an adequate supply of fluid to the original geothermal systems. However, most lacustrine deposits in the western United States are not associated with epithermal mineralization and most modern lakes are not associated with geothermal activity. We conclude that volcanism, tectonism and large fluid reservoirs cannot act independently to produce epithermal mineral deposits, but must act in concert.

To develop a more complete understanding of these interactions we have selected to examine the Aurora-Bodie volcanic field, California-Nevada, just north of Mono Lake, California. Volcanism commenced in the present-day Bodie Hills and eastward ~ 17 Ma ago with eruption of calc- alkaline andesite, dacite, and rhyodacite onto a peneplained surface. Initial geothermal activity followed at ~ 13 Ma at Masonic in the northern Bodie Hills. Andesitic constructional volcanism was active in the Aurora District between 15.4-13.5 Ma (Kleinhampl et al., 1975) with associated andesite and rhyolite emplaced between 12.5-11 Ma.

During the Miocene a 35 km^3 complex of small alkali-calcic, high-potassium andesite to dacite stratovolcanoes and cumulodome complexes (13.3 +/-0.4 to 7.7+/-0.4 Ma) covered these older volcanics. Mineralization in the Aurora District was probably associated with the Brawley Peaks andesitic stratovolcano that was built between 15.4+/-0.3 Ma and 11.2+/-0.2 Ma. Alteration in the core of this edifice, resulting from geothermal activity, has been dated at 13.7+/-0.5 Ma (M.L. Silberman, pers. comm.). Two other geothermal events occurred at 11.0+/-0.2 Ma and 10.3+/-0.3 Ma, the latter forming the economic quartz-adularia veins in the Aurora district. Two distinct episodes of geothermal activity at 7.8+/-0.2 Ma and 7.2+/-0.1 Ma (Silberman et al., 1972), produced economic mineralization in the Bodie District. These episodes are geochemically and mineralogically distinct (based on data in Brown, 1907) and were focused on the southeast flank of the alkali-calcic Bodie Mt.-Potato Peak stratovolcano and nearby domes. Bimodal Pliocene (<5.7 Ma) to Pleistocene (~250,000 yrs) andesitic and basaltic volcanic rocks were erupted from small, readily recognizable vents associated with rhyolitic domes and flows (Kleinhampl et al., 1975). The youngest epithermal mineralization in the region is associated with the early Pliocene activity at ~ 5 Ma at Borealis on the flank of the Wassuk Range. Recent geothermal activity can be observed in the environs of the town of Bridgeport. There are two prominent tectonic features in this region. First, the Fletcher Valley-Coal Valley basin bounded by northeast-trending faults on the southern margin and northwest-trending faults on the west and east margins. This structural basin developed between ~13 Ma and the present. It was lake-filled between ~ 12.5 Ma and 7 Ma, and was intermittently lacustrine to 5-4 Ma (Gilbert and Reynolds, 1973). The gradual loss of the lacustrine environment records the uplift of the Sierra Nevada and continuation of vertical tectonics in the local area. Second, a northeast-trending arch forms the northern margin of the Mono Basin. The Aurora, Bodie and Borealis Districts are aligned along this structure. Summarily, volcanism has been episodic in the Bodie Hills for the past 17 Ma, and the area has been tectonically active since 13 Ma. Nevertheless, mineralization is restricted to the interval 13-5 Ma, with the most productive geothermal systems active in the period 11-7 Ma. Consequently, the Aurora-Bodie volcanic field is an appropriate initial test area because of 1) the presence of several ages of epithermal mineralization associated with Neogene volcanism; 2) a well defined structural setting; 3) the presence of dated lacustrine sediments associated with mineralization, and; 4) the availability of data on climatic conditions during the Neogene.

AVIRIS data is being used to help answer a number of questions including: 1) What is the timing of geothermal activity, and how many individual geothermal episodes exist in the Aurora-Bodie area? 2) How were the epithermal systems aerially redistributed, how extensive is each hydrothermal event, and to what igneous events can they be related? 3) What was the relation of the geothermal activity to the volcanic landforms, and timing of structural activity, and can the paleohydrology be reconstructed from this information? 4) Do the different precious- and base-metal paragenesis reflect temporally/spatially distinct phases of mineralization or only spatially separated parts of one event?

IMAGING SPECTROMETER DATA

The AVIRIS data used in this study was collected on August 20, 1992 and consists of two flight lines containing 760 km^2 of data. A combined method of radiative transfer modeling and empirical ground calibration site reflectance were used to correct the flight data to surface reflectance (Clark *et al.*, 1996). This method corrects for variable water vapor in the atmosphere and produces smooth spectra with spectral channel to channel noise approaching the signal to noise of the raw data. Thus, the data can be compared to standard laboratory measurements. The calibration sites consisted of two maars that were vegetation free and appeared mineralogically uniform. Samples from the maars were collected after the overflight and measured on the USGS laboratory spectrometer (Clark *et al*, 1990b). The spectra of the calibration sites are spectrally bland and serve as an ideal calibration standard.

TRICORDER ANALYSIS

Clark *et al.*, (1990a, 1991,1996) developed a new analysis algorithm that uses a digital spectral library of known reference materials and a fast, modified-least-squares method of determining if a diagnostic spectral feature for a given material is present in the image. This algorithm is called "tricorder." The tricorder analysis compares continuum-removed spectra from the remotely sensed data, to a database of continuum-removed spectral features from the reference spectral library (Clark et al., 1993). Multiple features from multiple materials are compared and the material with the closest match is mapped. The algorithm does not force a positive match which makes it different from many other algorithms in use. The tricorder algorithm attempts to map only minerals included in the reference database.

For the present study we mapped minerals based on the presence of absorption features in the ~0.45 μm to ~1.0 μm, 1.5 μm, and 2.2 μm to 2.3 μm wavelength region, which represent the visible and near-infrared portions of the elector-magnetic spectrum. In this Dadaist we looked for 165 different materials. The materials we mapped for included silicates, phyllosilicates, sulphates, carbonates, amorphous iron compounds, cyanide compounds, as well as mineral mixture which contain two or more of these individual mineral groups.

Absorption bands in the visible portion of the spectrum (~0.4-0.8 μm) are caused by electronic processes including crystal field effects, charge transfer, color-centers, and conduction bands. The absorptions resulting in the visible portion of the spectrum involve elements of the first transition series which have an outer unfilled d-shell in their electronic distribution. The energy levels are determined by the valence state of the element, its coordination number and its site symmetry. Differences in these parameters are manifested in individual diagnostic absorption bands. Absorptions in this wavelength region are commonly associated with the presence of iron in the mineral structure.

Near-infrared radiation (1-2.45 μm, in this study) absorbed by a mineral is converted into molecular vibrational energy. The frequency or wavelength of the absorption depends on the relative masses and geometry of the atoms and the force constants of the bonds. There are two main types of molecular vibrations: stretching and bending. A stretching vibration is a movement along the bond axis which either increases or decreases the interatomic distances. Bending vibrations consist of a change in the angle between bonds with a common atom or the movement of a group of atoms with respect to the remainder of the molecule, but without movement of the atoms in the group with respect to one another (Silverstein et al., 1981). Only vibrations that result in a change in the dipole-moment of the molecule will be infrared active.

Absorption features in the 2.2 to 2.3-μm region result from a combination of the OH-stretching fundamental with either the Al-O-H bending mode absorbing at approximately 2.2 μm, or Mg-O-H bending mode absorption at 2.3 μm. At high resolution these bands also appear as characteristic multiple, complex absorption features. Based on previous work (King and Clark,1989, Clark et al., 1990b, Clark et al., 1993), it is known that the strength, position and shape of these features is a function of the mineral chemistry.

In this study we searched for 54 minerals plus 5 vegetation and water and snow mixtures with absorption features at wavelengths near or less than 1.0 μm. We mapped 12 of the 54 potential minerals in significant areal extent. Comparison of spectra of these minerals extracted from the remotely sensed data with our laboratory standards shows good matches.

To detect the presence of minerals that have absorption features in the 2.2-2.3 μm wavelength region we used 93 material standards including minerals, snow and ice mixtures plus vegetation standards. Of these 93 standard materials we detected 15 different phases of significant areal extent.

In addition, we have mapped 13 different types of vegetation plus vegetation water content and relative stress. These measurements were based on absorption features in both the 1 μm and 2 μm wavelength regions.

DISCUSSION

The AVIRIS data provides new insights into both mineralogical and structural evolution of the of the Aurora-Bodie volcanic field. The AVIRIS data delineates large tectonic features and areas of epithermal alteration. At least five major areas of epithermal alteration not associated with mining districts, in addition to areas of alteration associated with the mining districts of Aurora and Bodie, have been identified in the AVIRIS scenes. Mineral maps based on absorption features primarily in the 1 μm wavelength region, resulting from the presence of Fe-bearing minerals (electronic absorption features), and maps based on the presence of alteration associated with the presence of absorption features in the 2.2-2.3 μm region (vibrational absorptions) define these areas of alteration. Data analysis suggests that geologic information on the composition of parent rock can be gained from comparing the distribution patterns of the 1 μm and 2 μm absorption feature maps. It appears that Fe-bearing minerals without the association of materials having a 2 μm absorption feature occur in regions of basaltic composition and the absorptions result from the superficial Fe-staining on the rocks. The area on the west side of Beauty Peak provides an example. Similarly, areas that show alteration materials having a 2 μm absorption feature, and lack alteration minerals having a 1 μm absorption feature, appear to be Fe-poor rhyolitic or dacitic rocks. However, field verification will be necessary to confirm these correlations.

The area of oldest alteration (observed on the eastern edge of the AVIRIS scenes) is associated with the Aurora mining district (15.4-11.2 Ma) and youngest (observed on the western most edge) is in the region of Travertine Springs near Bridgeport. Between these two locations are the 4-5 other areas of alteration which are intermediate in age. The Bodie mining district is mineralogically distinct on the AVIRIS scene. However, the heavy reworking of the upper most geologic material during the mining process suggests that it will be difficult to extract information on the type and extent of alteration from the AVIRIS data. Other areas of epithermal alteration occur near Brawley Peak, Beauty Peak, Paramount Creek, Aurora Canyon, and Murphy Spring. These areas differ in size, amount of a particular mineral and the spatial relation between the mineral phases, but all are similar in the hematite, Fe-bearing minerals, amorphous iron oxide, sulphates (including alunites and jarosite), phyllosilicates (montmorillonite and kaolinites), and chalcedony. Many of these areas of alteration are associated with tectonic features.

The most obvious tectonic feature in this data set is a prominent Sierra front range fault that bounds the western most edge of the data set. Zones of alteration (Travertine Hot Springs and Murphy Springs) seem to be bound by this large fault. Other areas of alteration (Paramount Creek and Aurora Canyon) seem to be associated with a fault or series of faults that extends (NE to SW trending) nearly the length of the data set.
Faulting, to a lesser extent, is associated with the other areas of epithermal alteration.

SUMMARY

Although we are at the preliminary stage of relating the results of the AVIRIS mapping with age dating and field verifications, we are confident that imaging spectroscopy data is a valuable tool for providing new first-order insights into the aerial extent and mineralization associated with epithermal systems. These insights, combined with other field studies, mineralogic and age-dating techniques, can be used as a predictive tool in assessment studies and in the development of new exploration strategies.

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